Algorithms for constructing optimal paths and statistical analysis of passenger traffic

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Abstract. Several existing information systems of urban passenger transport (UPT) are considered. Author's UPT network model is presented. To a passenger a new service is offered that is the best path from one stop to another stop at a specified time. The algorithm and software implementation for finding the optimal path are presented. The algorithm uses the current UPT schedule. The article also describes the algorithm of statistical analysis of trip payments by the electronic E-cards. The algorithm allows obtaining the density of passenger traffic during the day. This density is independent of the network topology and UPT schedules. The resulting density of the traffic flow can solve a number of practical problems. In particular, the forecast for the overflow of passenger transport in the «rush» hours, the quantitative comparison of different topologies transport networks, constructing of the best UPT timetable. The efficiency of the proposed integrated approach is demonstrated by the example of the model town with arbitrary dimensions.

1. Transport network and its modeling

In a small town, a car is capable to satisfy much of the personal travel demands. Increasing size of the city leads to the growing need for other modes of transport. Traditional types are tram, trolley, bus, metro, taxi, rental cycling, and improving pedestrian comfort posts. With growth of the economic and environmental benefits of the non-car modes of transport, their deployment leads to creation of complex transport systems and, especially, their effective information support. Moreover, adequate structure and organization of transport are extremely important for the transport systems of large cities and agglomerations [1].

Existing urban public transport network components have varsions degrees of stability. Thus, for example, modernizations of the laid communications are performed extremely rare. The leader in management of the urban passenger transport-ray (UPT) in Yekaterinburg is the municipal enterprise «Tram and trolleybus management (TTM)». The enterprise also rarely modifies structure of the existing routes. The most flexible component is the schedule of routes. Determination quality of the public transport networks needs the criteria for comparing different versions of these UPT networks and schedules. Substantiation of necessity of modifying the network of routes and schedules needs new quantitative assessments (estimations) of the quality.

Ignoring of determination such estimations and arbitrary modification of the UPT components can lead to appearing the frequent traffic congestion, overloading/underloading separate lines, nodes and transport units, and increasing in the number of accidents [2]. Moreover, jams may occur inside the vehicle in the form of overloading of the machine with a corresponding reduction of the ride comfort. These strains are also to be included into modeling.

Improving the UPT management system must be accompanied by tracking changes of all its components. Unwarranted use of rather complex experiments on real systems may have a negative impact on the UPT. The UPT development is recognized as the first and most effective measure to combat traffic jams.

The difficulty of the traffic flow formalization (including public transport) has become a major cause of inconsistency of the research results and requirements of practice.

Under these conditions, the UPT improving is impossible without adequate mathematical models and numerical experiments.

The novelty of the work is to develop an algorithm for finding the optimal transport routes for a model city using the model schedules and model of the metropolis transport network.

2. Scientific approaches to the study of traffic flows

There are models designed for prediction of the transport and passenger flows in networks with known geometry and characteristics and known placing various objects on the territory [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. Models of this type are used to support decisions in the field of urban planning, to analyze the impact of various measures on the organization of movement, to choose alternative development projects and other transport network, and so on.

Our model of passenger flows uses optimal strategies, since the user of public transport often chooses his path to the target point according to some optimality criterion. Preference is given to the criterion of the minimal time of attaining the goal. This criterion and another one (of the shortest path) can be taken with some weights as the «summary» criterion.

3. Information on the public transport

Enlargement of public transport systems requires sophisticated JavaScript passenger information about modes of public transport [16, 17, 18, 19].

Existing information systems (IS) do not provide residents of Yekaterinburg with complete information necessary for a comfortable and efficient use of the UPT. In particular, the information services do not give to a passenger the optimal path with respect to the start time, driving situation, and the current schedule.

Using of the optimal path, passenger in the IS could have social and economic benefits for all major Russian cities including Yekaterinburg.

Among the existing indicators (characterizing the transport system of the city and directly related to the quality of the UPT) are such groups of indicators as Planning, Performance traffic, and Mobility [20]. In the latter group, the most interesting for us are the following ones: the «average travel time» and the «average length of travel by public transport». However, these criteria are integral and does not contain any algorithmic component. They do not take into account the quality of services rendered to a concrete passenger.

We offer new quality criteria of the UPT activity. These criteria are passenger oriented and contain algorithmic components. Our information system implements intelligent services related to optimization of the passenger travel time depending on the schedule of vehicles. In foreign metropolitan areas [16], in contrast to the Russian cities [17, 18, 19], such services are the norm.

4. Problem of accounting the traffic situation in the UPT information systems

Effectiveness of the UPT falls significantly in the case of overloading the transport networks. Neither one system is able to precisely predict the traffic jams and their behavior even for short periods. This is due to the following properties of traffic:

- forecast of the stochastic traffic flow is possible only with a certain probability, as it directly depends on such random factors as weather conditions, accidents, etc.;
- non-stationary traffic flows and fluctuations in their characteristics occur in at least three cycles: daily, weekly, and seasonal;
- behavior of each individual driver (of a traffic vehicle) is unpredictable.

Thus, inclusion of data on the traffic jams into the information systems of public transport does not lead to diminishing the role of a random factor. Improving the accuracy of the information about the work of the UPT is in strict keeping at the schedules. So, the authority should recognize the absolute priority of public transport in the urban passenger transport. The quality of public transport is one of the components of quality of the city administration.

5. Model properties

The authors developed a model UPT network, close to the real conditions of the metropolis.

Implemented model has the following properties:

- stops and routes are shown in a graph;
- model uses the tram and trolleybus routes with possibility of adding new types of the passenger transport;
- timetables for each traffic route are implemented;
- visual representation of the city transport network;
- finding the optimal path from the start stop to the end one with respect to the time of arrival of the passenger at the starting point; at the same time, all transfers, the time spent on the trip and waiting for transport should be shown.

The model allows determining the following indicators:

- minimum number of transfers, with which the passenger with guarantee can get from one stop to another provided that the transport is moving strictly according to the schedule;
- the average waiting time for a passenger at each stop.

6. Mathematical model of the transport network, the algorithm and software implementation for finding the optimal route

Mathematical model of the transport network allows us to build the trajectories of the urban passenger transport of a model city.

Let X the set of stops numbered by natural numbers. A road section between stops i and j containing no other stops is called the stage P_{ij}. The stage is a directed section. The set of all existing stages is denoted as P. The tram routes are enumerated.

Trajectory of each route is a sequence of related stages

$$T(n) = \{P_{1,2}, ..., P_{m(n)-1,m(n)}\}, \tag{1}$$

where $m(n)$ is the number of stops in the route n, including the start stop and end one. Trajectory may contain duplicated stages.

Let a train of the route n came out from the initial stop at the instant t_{start}. The instant of its arrival at the next stops form a sequence

$$V(n, t_{\text{start}}) = \{t_1 = t_{\text{start}}, t_2(n, t_{\text{start}}), ..., t_{m(n)}(n, t_{\text{start}})\} \tag{2}$$

Let a route schedule is a pair of the route trajectory and the time sequence

$$G(n, t_{\text{start}}) = \{T(n), V(n, t_{\text{start}})\} \tag{3}$$

The route may have several schedules within a day.

Consider the algorithm for finding the optimal route based on the principle of dynamic programming. Let us a passenger be at the stop A at the instant t_{start} and needs to reach the stop B in a minimum time. His path can contain transfers.

Let the mark $M(i)$ for an arbitrary stop i is a pair of a schedule and the time of arrival at this stop for this schedule

$$M(i) = \{G(n, t_{\text{start}}), t_i(n, t_{\text{start}})\} \tag{4}$$

Mark of the stop i allows us to determine the route and a previous stop, from which we come to this stop from the i-one. A mark with the earlier arrival time overwrites the previous mark. The starting stop A has not a mark.

Marking the stops is carried out on the wave principle: the first considered stops located from A with a radius equal to one stage, then two stages, *etc*.

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The algorithm terminates when viewing all the stops of the last radius and none of the marks has not changed.

If the end stop *B* is marked with the time of arrival t_{end}, the view of stages coming from other adjacent stops and marked with the time later than t_{end} is not performed.

Check by increasing the radius, we came to some marked stop *i*. Let the time of new mark be worse than the time of the previous mark *M*(*i*). Then we keep this mark *M*(*i*), and further increasing the radius through the stop *i* is not performed.

Summary screen of the simulation example is shown in figure 1. Stops coincide with crossroads and are numbered from 1 to 400. The optimal trajectory is colored. The color changing (digits) indicates a transfer.

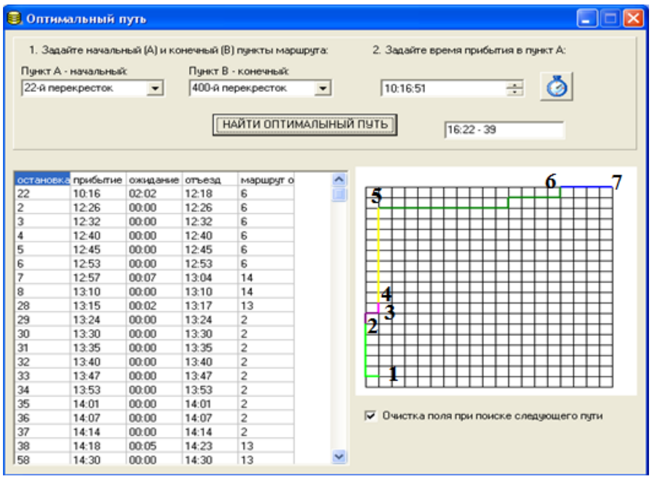

Figure 1. The result of searching for the optimal path.

In this paper, we demonstrate possibility of application of the pro-led calculations not for a single person, but for the entire population of the city. This allows one to get the experimental data and to calculate the new statistics quality UPT.

The simulation results show that the algorithm can be applied to the real transport network with real timetables.

7. Sensitivity analysis of the optimal path w. r. t. perturbation of the initial data

As a rule, passengers of the public transport do not have possibility to influence the route schedules, but rather are forced to adjust to them. For more convenient use of the UPT a passenger should know how the optimal path and minimum travel time vary when changing the initial conditions of the trip. Maybe, the passenger gets to its destination faster if he moves to the next stop with a large number of routes (sensitivity to perturbation of the starting point of the passenger path). Maybe, he should go out earlier (sensitivity to perturbation of the start time and end point).

We implemented the sensitivity analysis of the optimal solutions when the parameters of the original model vary slightly. Usually, such analysis is carried out in optimization problems in the technical, economic, and other fields.

Figure 2 shows changing in the time optimal path when changing the start time from the starting point. In the calculations, the actual tram schedule of Yekaterinburg was used.

The simulation results show: the start time being in the range of 15 h 32 min to 21 h 32 min, the minimum travel time from the stop of «Enthusiasts» to the stop «Peace» is changed from 30 min to 50 min.

High sensitivity is a disadvantage for the UPT and leads to the overloading on the optimal transport trajectories. Sensitivity coefficients should be among the quality criteria of the UPT timetables.

We investigated other important criteria for evaluating the UPT activities, such as covering the city, guaranteed travel time, number of transfers, waiting time, etc.

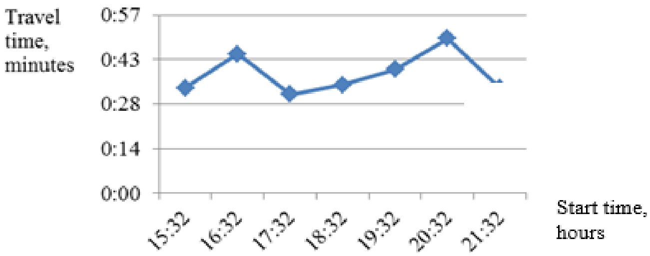

Figure 2. Analysis of dependence of the optimal path on the start time.

8. Statistical analysis of passenger flow

The UPT information system stores large statistical data related to the motion of passengers [21]. Traditional sources for this material are video cameras on the transport stops and in the interior of the passenger saloon. Processing this data allows counting the number of incoming and outgoing passengers.

We have implemented a different method. We developed analysis of system of the urban passenger electric transport on the basis of information about electronic travel payments and traffic navigation data of the mobile unit. The objective of the study is identifying the traffic flow with electronic fare payment and the navigation system of motion of the trams. We can determine the motion of passengers paying fares with an electronic card. The possibility of «gluing» of several transactions in a single itinerary for a passenger is realized; it solves the problem of the "last mile", i. e., the definition of the unknown place and arrival time of the passenger.

We have received a distribution of passenger flow using basic information about the motion of passenger: the time and place of the start and end points of his trip. Estimate of the distribution of urban the passenger electric transport carried out between the administrative areas of the city with reference to the routing scheme of the tram motion. Although the number of stops in each administrative district is different, this allowed us to determine the direction of motion of passenger traffic through several parts of the city.

The analysis is performed for the real traffic flow in the work and day time. The system works with incomplete input data (considered only one type of public transport) [22]. The grouping of stops on the administrative districts allowed building the OLAP-cube with information about the passenger path.

The statistical analysis cube allows us to define extremums of the passenger traffic, and the city administration can mitigate these extremums for modernization of the urban transport network.

9. Conclusions

An algorithm for finding the optimal route of the passenger is presented. The algorithm uses dynamic programming method, complicated by the presence of the time factor. Optimal routes form the first of three modules of UPT network analysis. The second module involves assessing correspondence matrix of passenger traffic using electronic e-cards. The passenger's transfers as he moves from the start to the end point of the path are glued into one route. This passenger route in practice is optimal. The third module will enable to calculate the quantitative assessment of the quality of the transport network topology and route schedules. The third module uses the correspondence matrix, resulting in the second module.

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